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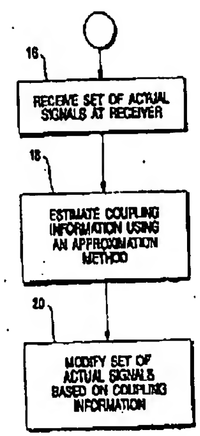
(54) Title: METHOD AND SYSTEM FOR COMPENSATING FOR COUPLING BETWEEN CIRCUITS OF QUADED CABLE IN A TELECOMMUNICATION TRANSMISSION SYSTEM

(57) Abstract

A method and system are provided for compensating for coupling between circuits of star-quaded cable by adaptively terminating the cable at a receiver. An approximation method uses a set of actual signals received (16) by the receiver (14) at one end of the cable to estimate (18) coupling information which, in turn, is utilized to modify (20) the set of actual signals. The modified set of signals estimate a set of transmitted signals received at the opposite end of the cable.



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METHOD AND SYSTEM FOR COMPENSATING FOR COUPLING BETWEEN CIRCUITS OF QUADED CABLE IN A TELECOMMUNICATION TRANSMISSION SYSTEM

Technical Field

This invention relates to methods and systems for compensating for coupling between circuits of quaded cable and, in particular, to methods and systems for compensating for coupling between such circuits in a telecommunication transmission system.

Background Art

Almost all North American telephone loop wire pair cable is multipair cable. These transmission circuits are formed by individually twisted pairs of copper wires that are stranded together.

In contrast, much of the European and Asian cable plant is constituted of quaded cable or circuits. Some building cables in North America are also quaded.

The elemental units in these cables are quads which are four insulated conductors or wires twisted together. The advantage of quading is that more circuits can be packed into a given cross-sectional area of cable. The disadvantage comes from the fact that the quad is geometrically unstable and the capacitances between the conductors in the quad are difficult to control. These factors lead to poorer crosstalk performance between circuits in the same quad.

Quaded cable can be made in two different configurations. In multiple twin quad, the two pairs that constitute the quad are individually twisted and then stranded together to effectively form a two-pair sub-unit. In star-quaded cable, the four conductors are twisted together. Most quaded cable is star-quaded. The cross-section of a typical star-quad is illustrated in Figure 1a. The natural modes of propagation of a perfectly constructed star-quad are obvious from the symmetry of the quad, and are illustrated in Figures 1b, 1c and 1d.

Two balanced pair modes, illustrated in Figures 1b and 1c, do not couple to each other because of the symmetry and opposite polarities of two conductors of the cable. The balanced pair modes are frequently referred to as "side circuits," a terminology descended from the use of multiple twin quad. Besides the balanced pair modes, one could use the phantom circuit of the balanced pair modes as shown in Figure 1d.

The polarities of the voltages on the four conductors guarantees that there would be no coupling between the phantom mode and the side circuits in a perfectly constructed star-quad. Thus, in such a quad, one would get three transmission circuits with four conductors. As far as coupling between quads is concerned, coupling between side circuits in different quads would be like dipole-dipole coupling as it is in multipair cables. Coupling between phantom circuits would be quadripole-quadripole coupling, which is generally looser than dipole-dipole coupling.

Unfortunately, it is essentially impossible to achieve the precision and stability of the quad structure to take advantage of the mode structure. The mechanical instability of the quad structure leads to coupling between circuits in the same quad. At high frequencies the coupling or cross-talk between conductors can be at unacceptable levels. The far end coupling, the coupling at the receive end of the cable, generated by the signal induced at the transmitted end, increases by 20 dB per decade. Further, the near end coupling induced on the transmitter by the transmitted signals increases by 15 dB per decade.

Consequently, phantom circuits are never used and side circuits in quaded cable have a shorter range at the higher frequencies used in modern services, such as Basic Rate ISDN.

Summary Of The Invention

An object of the present invention is to provide a method and system for compensating for coupling between the circuits of a quad, such as a star-quad, so that all three circuits on such a quad can be used with essentially no noticeable coupling between them.

Another object of the present invention is to provide a method and system for compensating for coupling between circuits of a quad, such as a star-quad, by adaptively terminating the circuits in an economical and simple way to improve the performance and capacity of such star-quads.

In carrying out the above objects and other objects of the present invention, in a telecommunication transmission system including a quaded cable (i.e. quad) having quads, a method is provided for compensating for coupling between circuits of the quads. The method includes the step of receiving a set of actual signals at one end of the quad. The set of actual signals is a function of a corresponding set of transmitted signals received at an opposite end of the quad and the coupling between the circuits. The method also includes the steps of estimating coupling information which is determined by the electromagnetic interactions between the circuits, modifying the set of actual signals based on the coupling information to estimate the set of transmitted signals, and transmitting the set of modified actual signals.

Preferably, the step of estimating includes an approximation method which utilizes the set of actual signals.

Also, preferably, the quad is a star-quad.

Further in carrying out the above objects and other objects of the present invention, in a telecommunication transmission system including a quaded cable having quads, a system is provided for compensating for coupling between circuits of the quads. The system includes means for receiving a set of actual signals at one end of the quaded cable. The set of actual signals is a function of a corresponding set of transmitted signals received at an opposite end of the quaded cable and the coupling between the circuits. The system further includes means for estimating coupling informa-

tion which is determined by the electromagnetic interactions between the circuits, means for modifying the set of actual signals based on the coupling information to estimate the set of transmitted signals, and means for transmitting the set of modified actual signals.

The above objects and other objects, features, and advantages of the present invention are readily apparent from the following detailed description of the best mode for carrying out the invention when taken in connection with the accompanying drawings.

Brief Description Of The Drawings

FIGURE 1a is a cross-sectional view of a typical star-quad;

FIGURE 1b is a cross-sectional view of a side circuit of such a star-quad wherein conductors two and four are at ground and conductors one and three are at +1 and -1 volts, respectively;

FIGURE 1c is a view similar to Figure 1b except conductors one and three are at ground and conductors two and four are at -1 and +1 volts, respectively;

FIGURE 1d is a cross-sectional view of a phantom circuit of such a cable wherein conductors one through four are at +1, -1, +1 and -1 volts, respectively;

FIGURE 2 is a block diagram flow chart illustrating the various steps of the method of the present invention; and

FIGURE 3 is a block diagram of a system for carrying out the method steps of the present invention.

Best Mode For Carrying Out The Invention

Referring now to Figure 2, there is illustrated in block diagram flow chart form the method of the present invention in a telecommunication transmission system. A portion of the transmission system is illustrated in Figure 3 and includes a transmitter 10, a quaded cable (i.e. quad), generally indicated at 12, having twisted conductors or quads and a receiver, generally indicated at 14. The method and system are provided for compensating for coupling between the circuits of the cable 12.

Referring again to Figure 2, at block 16 a set of actual signals are received at the receiver 14 at one end 17 of the quaded cable 12. The set of actual signals are a function of a corresponding set of transmitted signals received at an opposite end 19 of the quaded cable 12 from the transmitter 10 and the coupling between the circuits of the quad.

At block 18, coupling information which is determined by the electromagnetic interactions between the conductors is estimated utilizing an approximation method described in detail hereinbelow.

At block 20, the set of actual signals is modified based on the coupling information to estimate the set of transmitted signals.

Finally, the set of modified actual signals are transmitted by the receiver 14 along a line 24.

Referring again to Figure 1, the receiver 14 preferably includes a processor such as a microprocessor 26, a databus 28 and a system memory 30 which is used to store statistical information which correlates sets of actual signals received at the receiver to sets of transmittal signals transmitted at the transmitter 10. The statistical information is provided for all of the possible frequencies for the sets of signals.

Statistical information is used by the microprocessor 26 to estimate the coupling information.

The receiver 14 also preferably includes a circuit 32 for modifying the set of received actual signals based on the coupling information. The circuit 32 may include a set of amplifiers having gain factors which are adaptively controlled by the microprocessor 26 so that these outputs of the amplifiers provide an estimate of the set of transmittal signals transmitted from the transmitter 10.

<u>Characteristics Of Nominal Star Quads</u>

Since a star-quad has four conductors, the voltage transfer matrix from one end of the quad (x=0) to the other (x=l) is a four by four matrix:

$$\begin{bmatrix} V_1(l) \\ V_2(l) \\ V_3(l) \\ V_4(l) \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ a_{41} & a_{42} & a_{43} & a_{44} \end{bmatrix} \begin{bmatrix} V_1(0) \\ V_2(0) \\ V_3(0) \\ V_4(0) \end{bmatrix} \qquad (1)$$

The voltages in (1) are with respect to a putative remote ground at voltage zero.

In a nominal quad configuration, there is perfect geometrical symmetry within the quad and with respect to ground. Consequently, the coefficients in the transfer matrix satisfy the following symmetry:

$$a_{i,i+k} = a_{k,k+i};\ all\ k \qquad (2)$$

Consequently, (1) may be written in the form:

$$\begin{bmatrix} V_1(l) \\ V_2(l) \\ V_3(l) \\ V_4(l) \end{bmatrix} = \begin{bmatrix} a & b & c & b \\ b & a & b & c \\ c & b & a & b \\ b & c & b & a \end{bmatrix} \begin{bmatrix} V_1(0) \\ V_2(0) \\ V_3(0) \\ V_4(0) \end{bmatrix} \qquad (3)$$

The natural modes, or eigenvectors of this nominal quad are easy to identify. They are:

- The ground return mode, with all conductors at the same voltage, with an eigenvalue of a+2b+c.
- Two side circuits. One circuit has conductors two and four at ground, with conductors one and three at +1 and -1 volts, respectively. The other circuit has conductors one and three at ground, with conductors two and four at +1 and -1 volts, respectively. The eigenvalues of both of the side circuit modes is a-c.

- The phantom circuit. This mode has the four conductor voltages equal to +1, -1, +1, -1, respectively. The eigenvalue for this mode is a-2b+c.

The phantom circuit is usually the lossiest mode, and the ground return the least lossy. Since ground return modes in separate quads couple strongly to each other, they are never used for transmission, but are important to the theory of crosstalk coupling and inductive interference and impulse noise.

<u>Adapting Quad Terminations To Minimize Coupling</u>

Real quads are never nominal, but differ slightly from the nominal configurations as mentioned above. Thus, the side and phantom circuits of the quad will all be coupled loosely. The method and system illustrated in Figures 2 and 3 can be used to minimize the coupling between the modes.

For example, the normalized eigenvectors (mode vectors) of the nominal quad may be called (e_i). Then, the received voltage vector on a nominal quad would be v, given by:

$$v = \sum_{j=1}^{4} S_j e_j \qquad (4)$$

where the (S_i) are the transmitted data. Of course, if the ground mode is not used, one of the S_i would be zero. It is assumed, in writing (4), that the transmission effects have been equalized.

To extract the i^{th} data value (S_i) from the received vector, one can use the orthogonality of the normalized eigenvectors:

$$S_i = e_i^{\dagger} v \qquad (5)$$

Where

$$e_i^{\dagger}$$

is the transpose of e_i. Assuming that the mode vectors have been normalized. Of course, when the quad is not nominal, what is received is not S_i, but r_i, given by:

$$r_i = \sum_{j=1}^{4} C_{ij} S_j \qquad (7)$$

where the C_{ij} are unknown coupling constants. This equation may be written in matrix form as follows:

$$r = CS \qquad (8)$$

with obvious definitions for r, C and S. When the coupling is relatively loose, which is almost always the case, the diagonal elements in the coupling matrix, i.e., the C_{ii}, are close to one and the off-diagonal elements are (C_{ij} for $i \neq j$) close to zero. In this case, one may advantageously write (7) in the form:

$$r = (E + B) S \qquad (9)$$

where E is a unit matrix and B is small in the sense that it substantially reduces the magnitude of any vector that it operates on.

If one knew the cross-covariance of r and S, one could determine B and use this knowledge to cancel intermodal coupling. To see this, take the outer

product of both sides of (8) with $S^\dagger$ and take expected values to get:

$$\langle r\, S^\dagger\rangle = (E+B)\langle S\, S^\dagger\rangle \qquad (10)$$

which could be solved for B if $\langle r\ S^\dagger\rangle$ were known (where the brackets "< >" indicate expected value or statistical expectation). However, S is never known at the receiver 14 so that $\langle r\ S^\dagger\rangle$ cannot be obtained. However, one can write $\langle r\ S^\dagger\rangle$ in terms of what is known at the receiver 14. To do this, take the outer product of both sides of (8) with $r^\dagger$ and take expectations to get:

$$\langle r\, r^\dagger\rangle = (E+B)\langle S\, r^\dagger\rangle \qquad (11)$$

or equivalently,

$$\langle r\, r^\dagger\rangle = \langle r\, S^\dagger\rangle (E+B^\dagger) \qquad (12)$$

Combining (9) and (11) then yields:

$$\langle r\, r^\dagger\rangle = (E+B)\langle S\, S^\dagger\rangle (E+B^\dagger) \qquad (13)$$

This equation may be written in the form:

$$\langle r\, r^\dagger\rangle = \langle S\, S^\dagger\rangle + B\,\langle S\, S^\dagger\rangle + \langle S\, S^\dagger\rangle B^\dagger + B\,\langle S\, S^\dagger\rangle B^\dagger \qquad (14)$$

If this equation could be solved for B one would know the cable matrix C and would be able to make error free determination of the transmitted signal vectors. An approximate solution for (13) is easy to obtain. The clue to this is to note that, since B is small, the last term on the right in (13) is of second order in small quantities and may be neglected in obtaining an approximation, B_0, for B. Thus, B_0 is a solution of:

$$\langle r\, r^\dagger\rangle = \langle S\, S^\dagger\rangle + B_0\,\langle S\, S^\dagger\rangle + \langle S\, S^\dagger\rangle B_0^\dagger \qquad (15)$$

Equation (14) is an inhomogeneous set of linear equations in the elements of B_0 and may hence be solved by standard methods.

The error, $(B - B_0)$, between B and its approximant, B_0, is of second order in small quantities. To see this, (4) is subtracted from (13) to obtain:

$$(B_0 - B)\langle S\, S^\dagger\rangle + \langle S\, S^\dagger\rangle (B_0^\dagger - B^\dagger) = B\,\langle S\, S^\dagger\rangle\, B^\dagger \qquad (16)$$

Since $\langle S\ S^\dagger\rangle$ is not small or singular and the right side of (15) is of second order in small quantities, so is (B_0-B). Hence, B_0 is a good approximation to B.

If we use B_0 to obtain an estimate, $\hat{S}$, of the transmitted signal vector, one has:

$$r = (E+B_0)\hat{S} \qquad (16)$$

or, since B_0 is small,

$$\hat{S} = (E-B_0)\, r \qquad (17)$$

which is good to first order as a solution of (16). In a similar way, one could write:

$$S = (E-B)\, r \qquad (18)$$

Subtracting (17) from (18) one gets:

$$S - \hat{S} = (B_0-B)\, r \qquad (19)$$

Since it has been shown that (B_0-B) is of second order in small quantities, (19) shows that the error in $\hat{S}$ is of the second order in small quantities.

If the first order estimate B_0 needs to be improved, successively better approximation can be obtained by converting (13) into an iteration equation, which uses an earlier estimate for B in the second order term on the extreme right in (13) to obtain a closer approximation. Thus, one may write:

$$\langle r\, r^{\dagger} \rangle - \langle S\, S^{\dagger} \rangle - B_{n-1} \langle S\, S^{\dagger} \rangle B_{n-1}^{\dagger} = B_n \langle S\, S^{\dagger} \rangle + \langle S\, S^{\dagger} \rangle B_n \qquad (20)$$

If one sets $B_{-1}=0$, setting $n=0$ in (20) yields (14).

A relatively simple method and system has been described above for compensating for coupling between conductors in star-quaded cable. The method and system adaptively terminate star-quaded cable to substantially suppress coupling between nominal quad modes when there is loose coupling between them. An approximation method is described for estimating the transmitted signal using only information that is available at the receiver 14 and is good to second order in small quantities when the coupling is of first order. Thus, for example, if the coupling between modes is down, say, 20 dB, the adaptive termination would suppress it so that it was down about 40 dB.

Obviously, more elaborate adaptation procedures that require the transmission of information about received signal levels back to the transmitter 10, or the use of known training sequences, could reduce this error further.

While the best mode for carrying out the invention has been described in detail, those familiar with the art to which this invention relates will

recognize various alternative designs and embodiments for practicing the invention as defined by the following claims.

What Is Claimed Is:

1. In a telecommunication transmission system including a quaded cable having quads, a method for compensating for coupling between circuits of the quads, the method comprising the steps of:

receiving a set of actual signals at one end of the quaded cable, the set of actual signals being a function of a corresponding set of transmitted signals received at an opposite end of the quaded cable and the coupling between the circuits;

estimating coupling information which is determined by the electromagnetic interactions between the circuits;

modifying the set of actual signals based on the coupling information to estimate the set of transmitted signals; and

transmitting the set of modified actual signals.

2. The method as claimed in claim 1 wherein the step of estimating includes an approximation method which utilizes the set of actual signals.

3. The method as claimed in claim 1 wherein the quaded cable is a star-quaded cable.

4. In a telecommunication transmission system including a quaded cable having quads, a system for compensating for coupling between circuits of the quads, the system comprising:

means for receiving a set of actual signals at one end of the quaded cable, the set of actual signals being a function of a corresponding set of transmitted

signals received at an opposite end of the quaded cable and the coupling between the circuits;

means for estimating coupling information which is determined by the electromagnetic interactions between the circuits;

means for modifying the set of actual signals based on the coupling information to estimate the set of transmitted signals; and

means for transmitting the set of modified actual signals.

5. The system as claimed in claim 4 wherein the means for estimating includes means for performing an approximation method which utilizes the set of actual signals.

6. The system as claimed in claim 4 wherein the quaded cable is a star-quaded cable.

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Fig. 1a

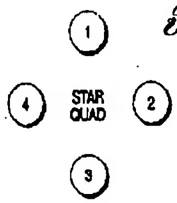


Fig. 1b

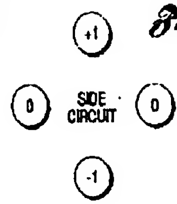


Fig. 1c

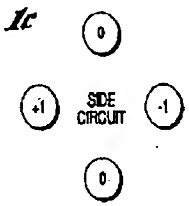
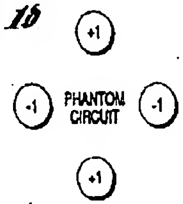


Fig. 1d



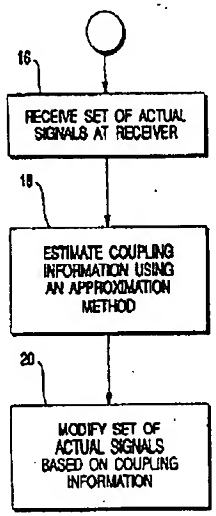
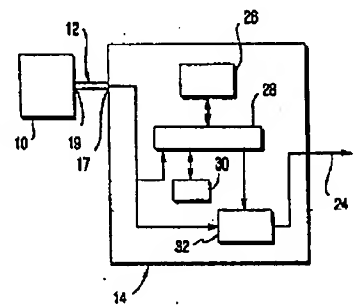


Fig. 2

Fig. 3



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INTERNATIONAL SEARCH REPORT

International application No. PCT/US94/00949

A. CLASSIFICATION OF SUBJECT MATTER
IPC(5) :Please See Extra Sheet.
US CL :379/414, 417; 375/14; 370/6
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED
Minimum documentation searched (classification system followed by classification symbols)
U.S. : 379/414, 416, 417; 375/14, 102; 370/6

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
APS
search terms: quad and star and cable and crosstalk

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X,P	US, A, 5,271,037 (Szechenyi) 14 December 1993, col. 1-3.	1-6
A	US, A, 5,088,423 (Streit et al.) 4 February 1992	1-6
A	US, A, 5,157,697 (Anvari et al.) 20 October 1992	1-6
A	US, A, 4,995,104 (Gitlin) 19 February 1991	1-6

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

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INTERNATIONAL SEARCH REPORT

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A. CLASSIFICATION OF SUBJECT MATTER:
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